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Intermittent Behavior in Oscillators

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Oscillators of all sorts may, for certain values of the parameters, show low-frequency disturbances. Usually the disturbance takes the form of a low-frequency interruption of the desired oscillation. By the method here presented it is possible to determine whether or not such intermittent behavior will occur in a given oscillator and what circuit modifications are required to promote stability. The intentional generation of a modulated wave by control of the low frequency behavior of an oscillator is also considered. Oscillators of the negative resistance type are not considered.

I. Introduction

IT HAS been known for a long time that all kinds of oscillators are subject to the trouble variously referred to as intermittent oscillation, motor boating, or squegging. In conventional circuits such as the Hartley the phenomenon is most likely to be observed if the grid leak and grid condenser are abnormally large. It is found that the time constant of this combination must be reduced as the frequency is raised and as the Q of the resonant circuit is decreased. At frequencies above a few hundred megacycles the problem of producing a practical circuit with suitable margin of stability is quite difficult.

With the advent of the oscillator having automatic output control the problem assumed a new aspect.[1, 2] By application of an amplified control circuit a high degree of constancy of output together with low harmonic output is obtained. Satisfactory operation is secured, however, only when suitable attention is given to the characteristics of the control circuit.

The intentional generation of pulses by means of intermittent oscillations of relatively high frequency has been studied to some extent, and circuits of this kind are employed in some television systems. Usually the high-frequency oscillation is limited to a small portion of the low-frequency cycle, the charge stored during this period being allowed to dissipate itself relatively slowly during the remainder of the cycle.

In all of these circuits satisfactory performance depends upon a proper proportioning of elements not directly associated with the operating fre-

[1] L. B. Argimbau, "An Oscillator Having a Linear Operating Characteristic," *Proc. I.R.E.*, Vol. 21, p. 14, Jan. 1933.

[2] J. Groszkowski, "Oscillators with Automatic Control of the Threshold of Regeneration," *Proc. I.R.E.*, Vol. 22, p. 145, Feb. 1934.

quency. When continuous oscillation is necessary it is desirable to provide adequate margin against intermittent operation. When intermittent operation is desired the opposite is true. In either case an understanding of the same general problem is necessary.

The present analysis applies only to oscillators of the feedback type. No method of extending it to cover negative resistance oscillators such as the Dynatron and the Transitron has been found. Relaxation oscillators as such are not considered here inasmuch as they are seldom affected by intermittent operation. No specific frequency limits apply but it is sometimes difficult at very high frequencies to achieve desirable values of the constants. At very low frequencies oscillators employing automatic output control are relatively unsuitable because their performance tends to be unduly sluggish.

The term linear oscillator is used to indicate an oscillator in which the range of operation is controlled within such limits that the harmonic content of the output is inappreciable.

The general equation describing a simple amplitude-modulated wave is

$$V = V_0(1 + m \sin 2\pi ft) \sin 2\pi Ft$$

This may be taken as defining the modulation factor m, a complex number which is limited to magnitudes between zero and one.

II. General Theory of Oscillation

It is found that three separate functions are necessary and sufficient for the operation of an oscillator of the feedback type.[3] These are indicated in the block diagram of Fig. 1.

The amplifier must be provided to overcome the losses of the rest of the system. The power output, if any, depends upon the fact that the output of an amplifier is greater than the input.

Selectivity must be provided to insure that the output has a definite frequency. Ordinarily a tuned circuit of relatively high Q is used although some excellent oscillators employ resistance-capacitance networks. The term filter is employed as being sufficiently general to include these extremes.

A limiter of some form is necessary to establish the level at which sustained oscillations occur. In many circuits the functions of amplifier and limiter are performed simultaneously in the vacuum tube. In an important class of oscillators the limiter is a thermal device such as a tungsten lamp. In the Meacham circuit the functions of limiter and filter are combined in a bridge employing a tuned circuit and a tungsten lamp.

To simplify the analysis it is convenient to assume that the amplifier of Fig. 1 is completely linear and operates with equal gain at all frequencies

[3] This topic is discussed more fully in "Hyper and Ultra-High Frequency Engineering," R. I. Sarbacher, and W. A. Edson, John Wiley & Sons, Inc., 1943.

from zero to infinity. Similarly the filter is assumed to consist of linear circuit elements and to have a definite curve of loss versus frequency. Associated with this loss characteristic is some specific phase characteristic.[4] The limiter is assumed to have a loss which is independent of frequency but which is explicitly related to the input (or output) voltage.

Although amplifiers having the ideal performance indicated are not physically realizable there are no new or unfamiliar concepts involved. Similarly the performance of passive networks, such as constitute the filter, has been extensively studied and is well understood. It is therefore appropriate to devote the following section to the third function.

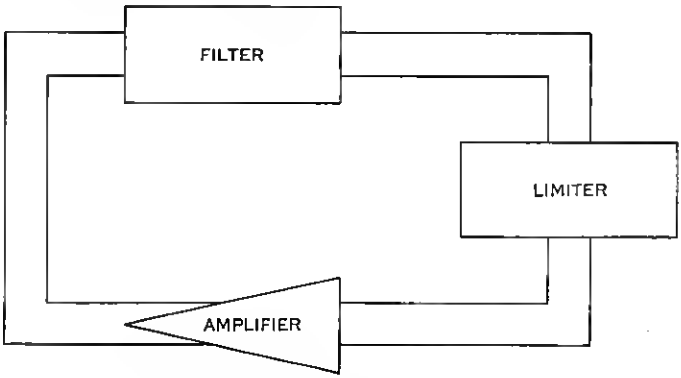

Fig. 1—Functional block diagram of an oscillator.

III. Types of Limiters

The limiters which are now in common use may be separated into four relatively distinct groups.

1. Vacuum tubes in which the gain is decreased by simple overload as the level of oscillation rises. This is the most common form of limiter.

2. Varistors in which the impedance depends upon the instantaneous value of current. Copper oxide, thyrite, and electronic diodes are examples.

3. Thermistors in which the resistance depends upon the rms value of current but does not vary appreciably during any one cycle. Carbon and tungsten filament lamps are the most common examples.

4. Vacuum tubes in which the gain is reduced by application of a bias which depends upon the level of oscillation. Usually the bias is developed by rectifying a portion of the output.

The limiters of the first two groups depend for their operation upon the generation of harmonic voltages and currents. The limiters of the second

[4] H. W. Bode, "Relations Between Attenuation and Phase in Feedback Amplifier Design," *Bell Sys. Tech. Jour.*, Vol. 19, pp. 421–457, July 1940.

two groups operate with very little harmonic distortion. The output of oscillators employing such limiters may, therefore, be made quite free from harmonic voltages. Oscillators of this sort are referred to as linear because the tube or tubes serve as simple Class A linear amplifiers.

IV. Criterion of Self Modulation

The block diagram of Fig. 1 is characterized by the fact that the separate elements are connected to each other in the form of an endless ring. The output may be assumed to come from any of the three junctions. It is this fact of closure which complicates the problem of oscillator study. For purposes of analysis it is convenient to open the loop as shown in Fig. 2. For this example it makes no difference where we choose to make the cut, but in actual circuits some caution must be exercised. This matter is dis-

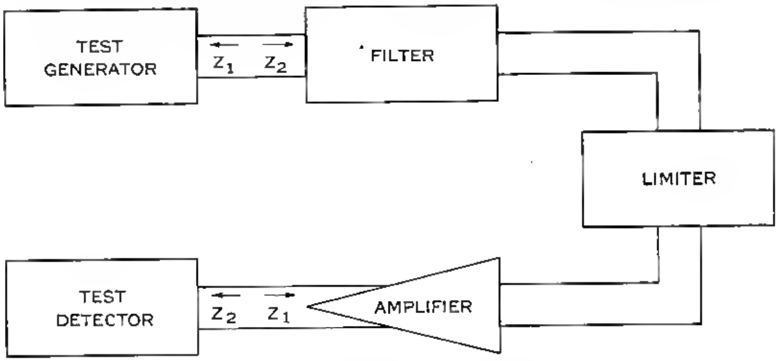

Fig. 2—Test for self-modulation in an oscillator.

cussed more fully later. It is also necessary to choose the impedances of the test generator and test detector so that the operation of the components of the original system is not disturbed.

If a continuous wave of suitable voltage and frequency is supplied by the test generator it will be found that the terminal voltage of the test detector is identical in magnitude and phase with that of the generator. In this condition the requirements which are fundamental to oscillators are satisfied. That is, the frequency and level at which oscillation should occur if the circuit were closed as in Fig. 1 have been established. The net phase shift of the system is zero and the net gain is zero.

Whether the oscillations so produced would be stable or interrupted is now determined by adding amplitude modulation of relatively low frequency and very small magnitude to the test generator. It is clear that this modulation will be transmitted through the amplifier, filter, and limiter to the test detector and that the phase and percentage of the modulation may both be

modified. By examining the transmission of a lightly modulated wave for various frequencies of modulation it is possible to determine whether or not the normal oscillation will be self modulated when the loop is closed as in Fig. 1.

The carrier is held constant at the frequency F and amplitude V for which the input and output are identical, and the frequency f of the modulation is varied from zero to infinity. In the following treatment it is assumed that the significant portion of the characteristic is observed for modulation frequencies small compared to F. The theory is simplified in this way without being seriously restricted in usefulness. The percentage of modulation must be held very low so as not to exceed the normal operating range of the limiter. The criterion is most conveniently stated in terms of the transmission of the modulation envelope which may be considered as a vector quantity.

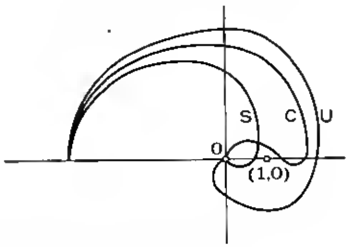

Fig. 3—Nyquist diagram showing magnitude and phase of loop transmission.
Legend: U is unstable
C is conditionally stable
S is absolutely stable

A plot of the vector ratio of output to input modulation for various frequencies is prepared as in Fig. 3. The system characterized by curve U is unstable and will generate a self modulated rather than a continuous wave. The system characterized by curve S is unconditionally stable and will be free from self modulation. The system characterized by curve C is conditionally stable and may generate either a continuous or an interrupted wave depending upon the manner in which the oscillation is started and other factors.

V. Analogy of the Oscillator to the Feedback Amplifier

The behavior of oscillators of the type here considered is entirely dependent upon feedback. It is therefore appropriate to review the fundamental principles which apply to feedback in general.

In the feedback amplifier, negative feedback is applied to improve the linearity, stability, impedance, or frequency characteristics. Considerable improvements in some or all of the properties may be secured if a consider-

able amount of negative feedback is applied and properly controlled. Positive feedback is sometimes used to increase gain or selectivity, but stability under such circumstances is poor. Any considerable amount of positive feedback results in oscillation.

The criterion by which stable feedback systems are distinguished from unstable ones has been presented by Nyquist and verified by others.[5, 6] A closed feedback system having input and output terminals is illustrated in Fig. 4. In Fig. 5 the loop is opened at some arbitrary point and a test

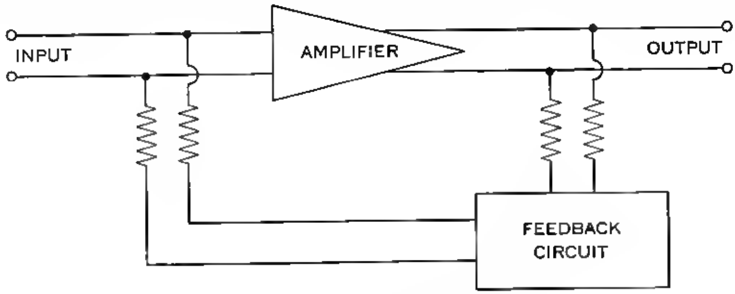

Fig. 4—Typical feedback amplifier.

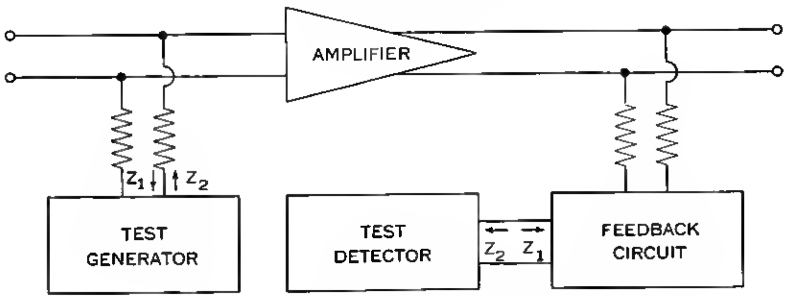

Fig. 5—Test for stability of feedback amplifier.

oscillator and detector are connected. Here as in Fig. 2 certain precautions as to impedance are observed. The test generator must produce a pure sinusoidal wave of such small magnitude that no part of the tested system overloads and the vector ratio of the detector voltage to the generator voltage is observed for a large number of frequencies. The polar plot of Fig. 3 applies directly to the feedback amplifier except that the radius vector represents the transmission of a simple wave rather than of an envelope.

[5] H. Nyquist, "Regeneration Theory," *Bell Sys. Tech. Jour.*, Vol. 11, pp. 126–147, Jan., 1932.

[6] E. Peterson, J. G. Kreer, & L. A. Ware, "Regeneration Theory and Experiment," *Proc. I.R.E.*, Vol. 22, pp. 1191–1210, Oct., 1934.

The conditions of absolute and conditional stability and instability are exactly the same as those already given.

It must be appreciated that Nyquist's criterion supplies no information as to the type or frequency of oscillations which will be generated by an unstable system. This is true because the analysis is limited to linear systems. The only information imparted is that a very small oscillation of some frequency will increase exponentially with time until the amplitude is limited by the action of some non-linear device. A small or relatively large shift of frequency may occur and the oscillation may be regular or intermittent. The present work extends the usefulness of Nyquist's criterion by using it in modified form to determine whether or not a particular unstable system (oscillator) has or lacks stability as to self-modulation. There is no apparent reason why a system lacking in both fundamental and envelope stability might not be analyzed a third time for the stability of the self-modulation.

VI. Analysis of an Oscillator having Automatic Output Control

Figure 6 presents a simple form of feedback oscillator having a separate rectifier as limiter. For small amplitudes of oscillation the tube operates in a linear fashion with cathode self-bias. No bias is produced by the diode rectifier until the peak voltage in the coil L_3 exceeds that of the bias battery B. All voltage in excess of this value is rectified, smoothed by the condenser C, and applied to the resistor r as bias. It is seen that a small percentage change in the output level may result in a large change in the bias. Accordingly an output which is quite stable with respect to the tube condition and applied voltages, except that of B, is to be expected.

The stability of this circuit with respect to self modulation is most conveniently tested by opening the oscillatory loop at the plate of the tube. In so far as the plate resistance of the tube is high with respect to that of the associated circuit it is not necessary to control the impedances of the test generator and detector extremely accurately. A block diagram equivalent to Fig. 6 is presented in Fig. 7. The conditions which must exist for the test of stability are shown in Fig. 8. In both those figures it should be noted that the gain control is actuated by the input, not the output, of the amplifier. It is therefore possible for a marked decrease of output voltage to result from a small increase of input voltage. This behavior is very different from that of the conventional, back-acting, automatic-volume-control amplifier in which the output change is in the same direction as the input change but of reduced magnitude. It is this difference which is the basis of most difficulty with amplitude controlled oscillators.

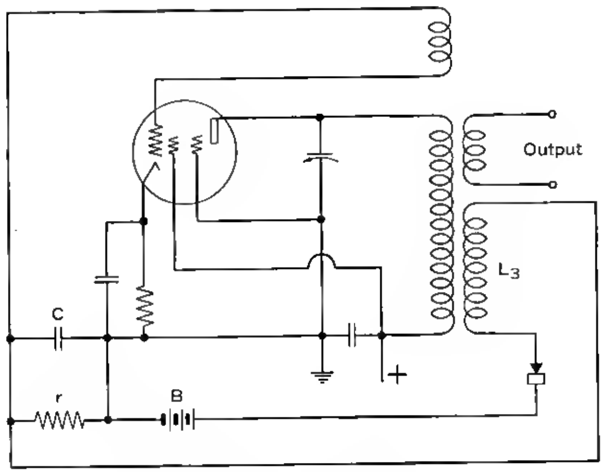

Fig. 6—Oscillator having automatic output control.

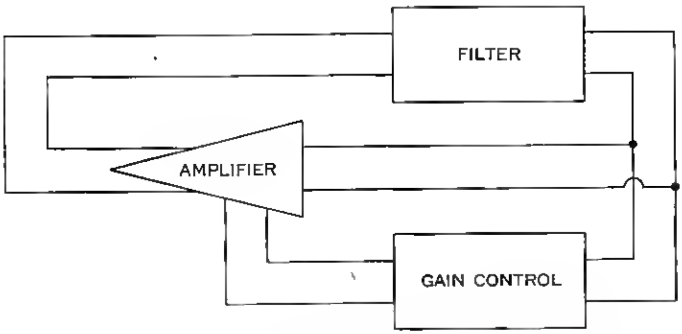

Fig. 7—Block diagram of automatic output control oscillator.

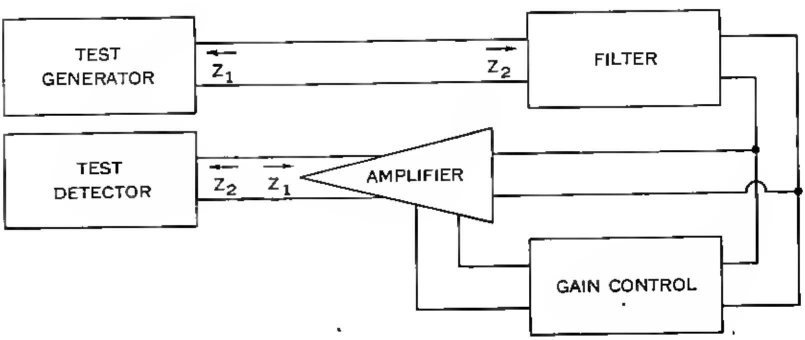

Fig. 8—Test for modulation stability of automatic output control oscillator.

Filter

The filter of Fig. 8 consists of only a single tuned circuit. Its transmission is readily represented in terms of the circuit Q by the familiar universal resonance curve. The transmission of a modulated wave through such a passive network is conveniently determined by separating the wave into its carrier and two sidebands. The carrier will be the frequency F corresponding to zero phase shift which, in this case, is also the frequency of maximum transmission. The sidebands will be shifted in phase by equal

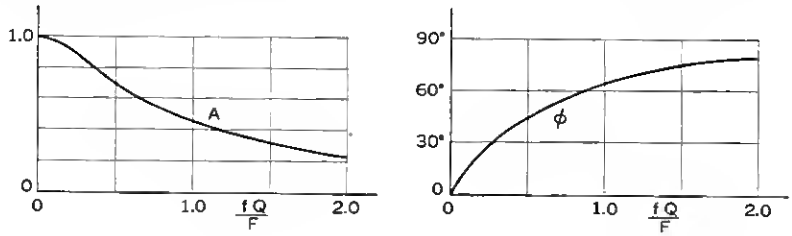

Fig. 9—Envelope transmission of a modulated wave through a single tuned circuit of selectivity Q.

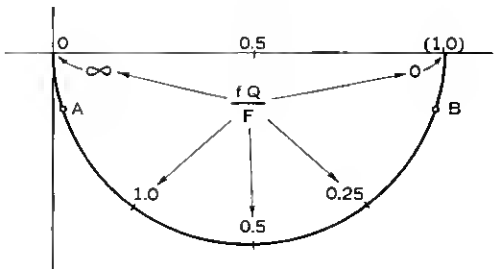

Fig. 10—Data of Fig. 9 plotted in polar form.

and opposite amounts and attenuated according to the frequency f by which they differ from the carrier. This behavior is interpreted in Fig. 9 as transmission and phase shift of the envelope. It is seen that the transmission approaches zero and the phase shift approaches 90° as the modulation frequency is indefinitely increased. The same data is presented in polar form in Fig. 10. Specifically Fig. 10 shows the vector ratio of the modulation factor m of the output wave to that of the input wave for all frequencies. In Fig. 9 the magnitude and phase angle of the ratio are shown separately.

Limiter

The limiting action of the tube and diode combination is determined by direct circuit analysis. For very low modulating frequencies the condenser

C of Fig. 6 serves only as a high-frequency by-pass; the direct voltage across r being the instantaneous difference between the peak voltage induced in L_3 and that of the stabilizing battery B. For very high modulating frequencies the modulation as well as the carrier is by-passed by C and no modulation voltage appears across r. Thus the bias is constant and the output wave is identical with the input wave. This corresponds to an envelope transmission of $(1, 0)$. For intermediate values of the modulating frequency the voltage developed across r varies in magnitude and phase approximately as if a constant current of the modulating frequency f were applied to r and C in parallel.

The output of the amplifier depends not only upon the bias developed across r but also upon the input. For systems having a large amount of control the action of the bias is predominant. Thus for a low modulating frequency the variation of the bias overpowers the initial modulation, the phase of the modulation is reversed, and the percentage magnified by the

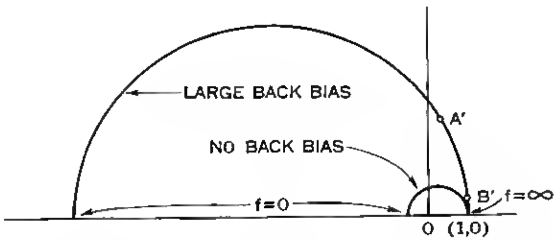

Fig. 11—Envelope transmission of a modulated wave through controlled amplifier.

action of the limiter. In Fig. 11 the envelope transmission is plotted in polar form for conditions of relatively large and relatively small amounts of control.

Loop Transmission

The separate diagrams of Figs. 10 and 11 are combined in Fig. 12 to determine the stability of the system. For any chosen frequency f the vector of Fig. 10 is multiplied by the vector of Fig. 11 corresponding to the same frequency to locate one point of Fig. 12. The resultant vector has an angle which is the sum of the two component angles and a magnitude which is the product of the two component magnitudes.

It is seen that the loop may be made to cross the axis considerably to the left of the point $(1, 0)$ if the points A and A' of the previous figures correspond to the same frequency. Similarly the loop may be made to come very close to the point $(1, 0)$ by increasing the size of C or lowering the Q of the tuned circuit so that the points B and B' correspond to the same frequency. With the circuit elements drawn in Fig. 6 the stability margin

may be reduced to zero, but actual looping of the point (1, 0) is not indicated. Parasitic elements, not here considered, can readily affect the performance enough to produce instability.

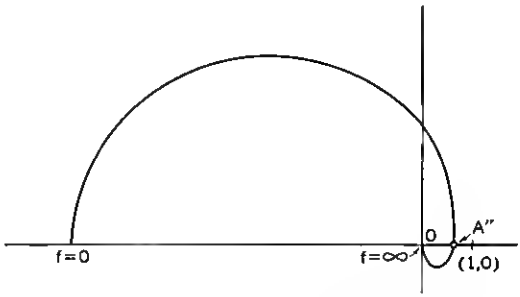

Fig. 12—Nyquist diagram applying to Fig. 6.

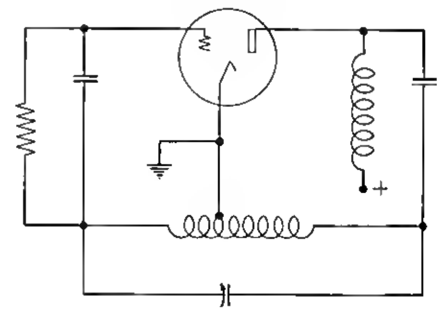

Fig. 13—Hartley circuit.

VII. Analysis of the Hartley Oscillator

The familiar Hartley Oscillator circuit is shown in Fig. 13. In this arrangement the tube serves as amplifier and limiter by the action of overloading. Harmonic voltages and currents are produced but if the selectivity of the tuned circuit is high the voltage returned to the grid of the tube is nearly sinusoidal.

The stability of this circuit is tested in exactly the same way as was that of the previous circuit. The loop is opened at the plate of the tube to determine the transmission of a modulated signal. If, as is usually the case, the coupling of the coil is close, the filter reduces to a single tuned circuit. The limiting action results from bias produced by rectification at the grid. Accordingly the block diagram of Fig. 7 is directly applicable, and the behavior of the filter is correctly given by Fig. 9.

Generally the circuit operates in class "C" with high bias and large grid

voltage swings. If the time constant of the grid-leak-condenser combination is long in comparison to the period of a modulation cycle the bias will not be able to follow the applied voltage and the modulation of the output will be larger than that of the input. Moreover it is in phase with that of the input. When the modulating frequency is low the bias is able to follow the level of modulation and the output modulation is very small. Thus the transmission of a modulated signal is greatest at high modulating frequencies, and the modulation output is in phase with the input. Because of the

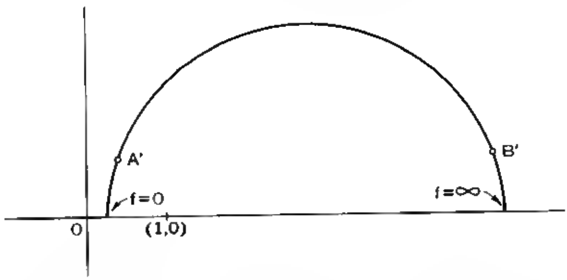

Fig. 14—Envelope transmission of a modulated wave through a grid-leak-biased Class C amplifier.

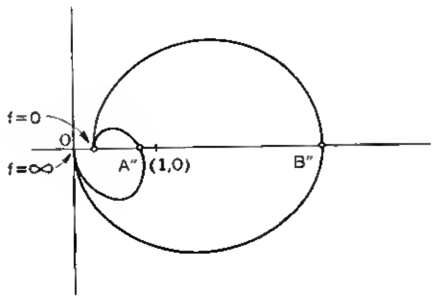

Fig. 15—Nyquist diagram applying to Fig. 13.

action of the grid-leak-condenser network a phase shift at intermediate modulating frequencies occurs. This behavior is represented in polar form in Fig. 14.

The stability of the system is determined by combining in Fig. 15 the separate diagrams of Figs. 14 and 10. As in the previous system a thoroughly stable system results if the element values are such that the points A and A' of Figs. 10 and 14 correspond to the same frequency. If on the other hand the elements are such that B and B' correspond to the same frequency the curve loops $(1, 0)$ indicating instability. In general stability is

promoted by increase of the Q of the tuned circuit and by decrease of the time constant of the grid-leak-condenser combination.

VIII. The Lamp Stabilized Oscillator

The circuit of Fig. 16 is of particular interest because the functions of amplifier, limiter, and filter are performed separately by units which are readily identified with their functions. The present method of analysis was developed in connection with this particular circuit. The output frequency and amplitude are both quite stable and the harmonic content of the output is low.

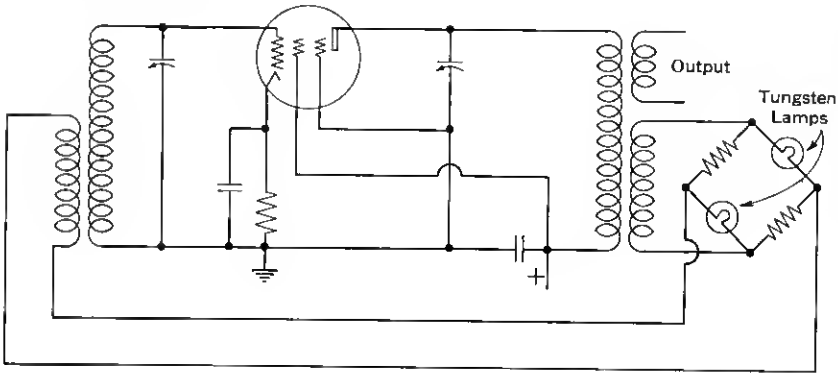

Fig. 16—Schematic diagram of lamp stabilized oscillator.

Under operating conditions the gain of the tuned amplifier, which is ordinarily in the order of 40 db, is equalled by the loss of the lamp bridge. The lamps operate at such a temperature that their resistance is slightly less than that of the associated linear resistors. If the gain of the amplifiers is for any reason somewhat reduced, the current through the lamps decreases, the temperature and resistance of the lamps is reduced, and the loss through the bridge is reduced to the new value of amplifier gain.

The d-c characteristic of a lamp bridge is shown in Fig. 17. A curve identical with Fig. 17 is observed if the measurement is made with an alternating current whose period is very short in comparison to the thermal time-constant of the filaments. Up to L the operation is nearly linear. In the region of M the output is essentially independent of the input. At N the bridge is nearly balanced and a small percentage change in the input voltage results in a large and opposite percentage change in the output. It is thus seen that an alternating current having a small superimposed modulation of low frequency will result in an output having a considerably

larger percentage modulation in the opposite phase. When the modulation frequency exceeds a few hundred cycles the lamps are unable to follow the individual cycles and the output wave is identical in form to the input. At intermediate modulating frequencies the transmission of a modulated wave

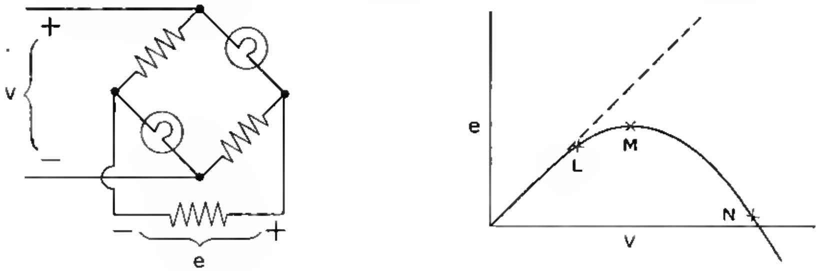

Fig. 17—D-C characteristics of a lamp bridge.

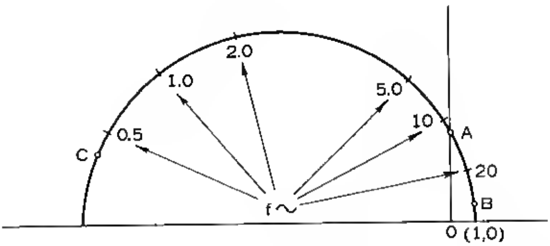

Fig. 18—Envelope transmission of a modulated wave through a lamp bridge.

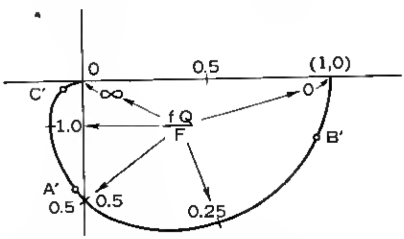

Fig. 19—Envelope transmission of a modulated wave through two similar tuned circuits of selectivity Q.

involves a phase sbift. The behavior of a typical lamp bridge is presented in Fig. 18.

If the Q of the grid and plate circuits are both relatively high the filter circuit may be taken as equivalent to two separate tuned circuits. The transmission of each is given by Fig. 9. The combined transmission of the pair is given in polar form in Fig. 19. Because two tuned circuits are

employed, the diagram of Fig. 19 differs markedly from that of Fig. 10. Specifically the phase shift corresponding to a given value of attenuation is greatly increased. As in previous cases the curve of over-all loop transmission may or may not loop the point $(1, 0)$ depending upon the relative frequency scales. Thus if the points A and A' of Figs. 18 and 19 correspond to the same frequency the Nyquist diagram passes near the point $(2, 0)$ indicating instability. If the points B and B' correspond to the same frequency the loop passes very near to the point $(1, 0)$ and instability is likely.

By making the tuned circuits very selective or by reducing the thermal time constant of the lamp circuit the points C and C' may be made to correspond to the same frequency. In this case the loop passes to the left of the point $(1, 0)$ and the system is absolutely stable. The same result may be secured more easily by making one of the tuned circuits much more selective than the other. This is ordinarily accomplished by increasing the Q and impedance level of the grid circuit while keeping the Q and impedance level of the plate circuit much lower so as to provide a suitable power output to operate the lamp bridge.

IX. The Varistor Stabilized Oscillator

A circuit which differs from that of Fig. 16 only in that the lamps are replaced by varistors is shown in Fig. 20. At low levels of oscillation the impedance of the varistors is relatively high, the loss of the limiter is low and the amplitude of oscillation rises. At some higher level the varistor impedance is reduced, the bridge approaches balance to the fundamental frequency, and a stable condition is reached. Because the initial unbalance of the bridge is opposite to that of Fig. 16 a reversal of phase is necessary to establish oscillation.

The stable condition reached differs from that of the lamp stabilized oscillator in that the varistor goes through its entire range during each high-frequency cycle. The lamp resistance changes by only a small amount during any one cycle, its resistance depending on an integration of many previous cycles. Two important facts arise from this difference. Harmonics are produced in the bridge and, in so far as the varistors face reactances of these harmonic frequencies, intermodulation may produce currents of fundamental frequency but shifted in phase with respect to the original. Thus the bridge may produce a phase shift which is a function of level of the oscillation frequency. A degradation of frequency stability results from such a condition. More important to the present problem is the fact that all modulation frequencies are transmitted alike. A small modulation is reversed in phase and magnified by an amount depending upon the bridge balance but not upon the modulation frequency.

Because the limiter introduces no phase shift it follows that the envelope loop transmission is merely an enlarged and reversed copy of that for the filter. This can loop the (1,0) point only if there are at least three shunt elements in the filter section. That is, instability can result only if the phase shift of the filter system exceeds 180° for frequencies relatively near the operating frequency. This circuit is therefore much less likely to produce intermittent operation than any other circuit here considered.

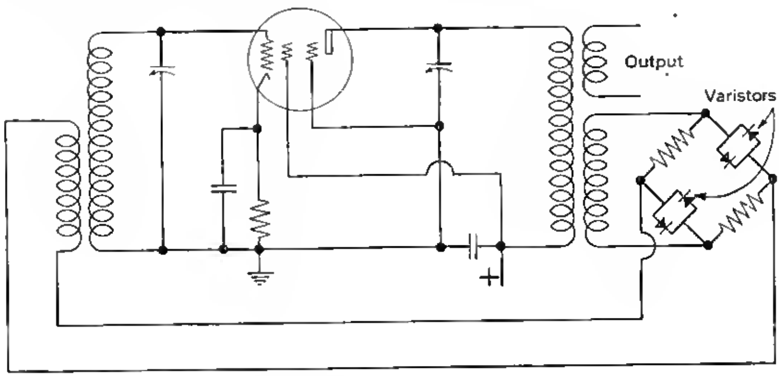

Fig. 20—Schematic diagram of varistor stabilized oscillator.

X. Negative Feedback in Oscillators

Because positive feedback is the necessary condition for the operation of an oscillator it is not obvious that the application of negative feedback is ever desirable. Actually it is frequently possible to introduce negative feedback into an oscillator with no loss of performance and under certain circumstances advantages are gained.

The circuit of Fig. 16 serves as a convenient example. Removal of the cathode by-pass condenser is likely to reduce the amplifier gain by about 6 db and to increase the stability of the gain with respect to applied voltages by a corresponding amount. Coincident with removal of the by-pass condenser the operating level drops a small amount, the bridge loss decreases 6 db to reestablish equilibrium, and the stabilizing effect of the bridge is cut in half. Accordingly the over-all stability of the output with respect to applied voltages is unchanged. The advantages gained are that the loss which must be held in the bridge is reduced so that stray reactances are less likely to disturb the operation, and that the harmonic content of the output is reduced.

Stated in a different way, the output stability of an oscillator using a non-feedback amplifier is limited in practice by the bridge balance which may be maintained. After this value of gain has been reached additional stability

may be secured by supplying increased inherent gain which is offset by direct negative feedback.

XI. Design of a Controlled Oscillator

To clarify the material already presented and to convey some additional concepts an oscillator having a large amount of control will be designed. The block diagram is to be that of Fig. 7 and the circuit is to be similar to that of Fig. 6.

It may readily be seen that the gain control must satisfy two fundamental requirements. It must deliver a d-c bias which increases rapidly with increase of the level of oscillation and it must not return any appreciable voltage of oscillation frequency. Otherwise the frequency will be affected by the elements in the control circuit as well as those in the filter, and the performance will be generally poor. Because of its balance a push-pull rectifier is helpful in meeting the latter requirement. The principal requirement is achieved by amplification and by the use of a constant counter emf or back bias. No bias is produced until the level of oscillation exceeds some threshold value. Above this threshold the bias increases approximately volt for volt with the peak value of the signal. The same amplifier which is used to increase the control may be used advantageously as a buffer so that appreciable power outputs may be produced without degrading the frequency or amplitude stability.

It will be assumed that a Q of 100 is available in the coil and that a frequency of one megacycle is to be generated. The transmission of a modulated wave in terms of the sideband displacement through such a one-circuit filter is shown in Fig. 21. Because the cutoff occurs very slowly it will be convenient to incorporate a rapid cutoff in the auxiliary filter of the gain control, thus avoiding an excessive phase shift at any one frequency.

The circuit features already discussed are shown in Fig. 22. A basic oscillator with a single tuned coil, a buffer amplifier having little selectivity and therefore contributing very little to the equivalent filter section, a source of biasing voltage, a balanced rectifier, and an auxiliary low-pass filter are shown. The condenser C is only large enough to allow the rectifier to be driven without serious loss at one megacycle. It has relatively little effect upon the modulation performance.

It is assumed that the buffer-amplifier, rectifier, etc. are so chosen that a modulation of very low frequency of one part per million applied at the plate terminal of the oscillator will result in a modulation of one part in a thousand returned to that point. This is equivalent to saying that the envelope gain is 60 db at low frequencies, and corresponds to 60 db of negative feedback in a conventional amplifier.

The auxiliary filter will be designed to approximate the attenuation and

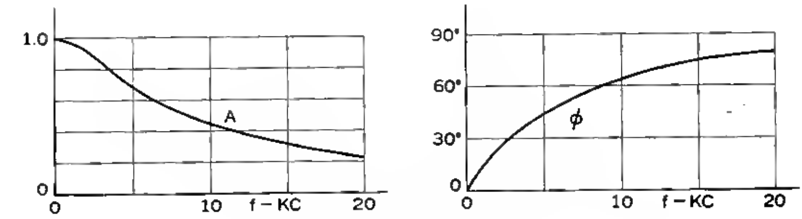

Fig. 21—Envelope transmission through tuned circuit.

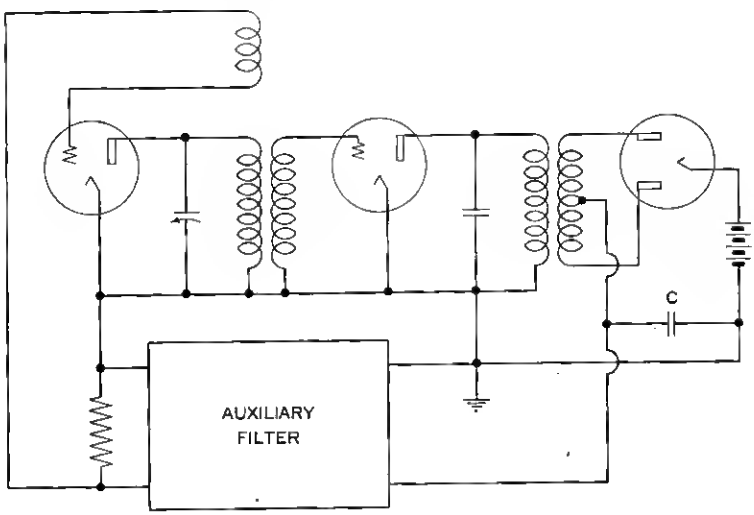

Fig. 22—Special A-V-C oscillator.

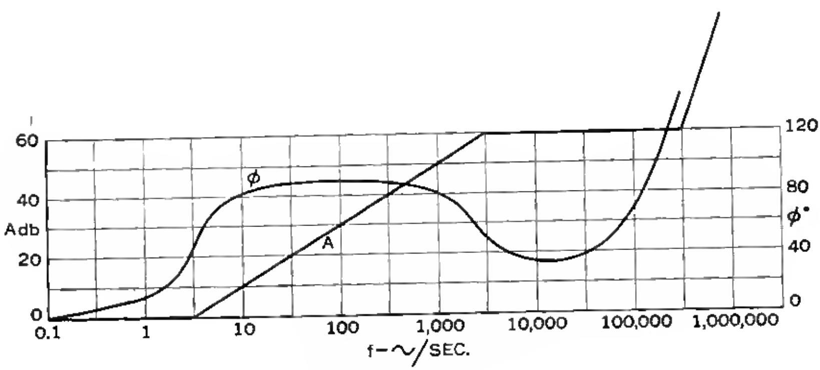

Fig. 23—Characteristics of auxiliary filter.

phase characteristics shown in Fig. 23. The choice of this particular shape is best explained by reference to Fig. 24 which presents the over-all envelope loop transmission of the system. It is seen that the phase shift is relatively constant at 90° over a wide band of frequencies and that the gain falls off approximately linearly over the same band. In particular the gain becomes zero around 5000 cycles whereas the phase does not reach zero below 500,000

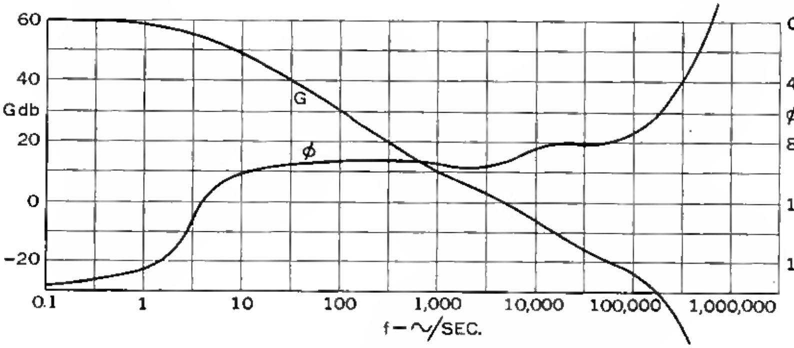

Fig. 24—Overall envelope transmission of Fig. 22.

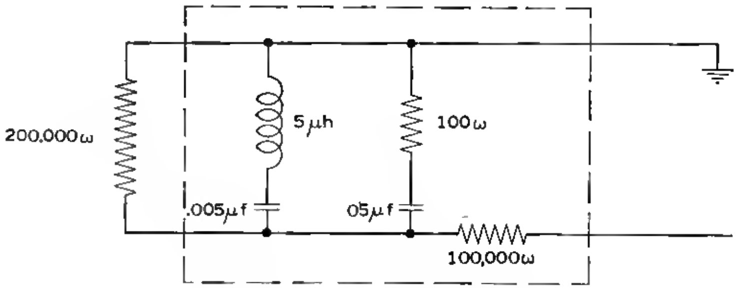

Fig. 25—Configuration of auxiliary filter.

cycles. In terms of Nyquist's criterion this represents a very stable system which is little disturbed by transient effects. A system having even greater stability could be achieved by beginning the cut-off at lower frequencies. It would then be found that the output was somewhat sluggish in reaching a new equilibrium after being disturbed. Such a behavior is not uncommon but is generally undesirable.

Elements which give approximately the characteristics called for in Fig. 23 are shown in Fig. 25. The peak of loss at one megacycle is contributed by the series resonant trap. The rest of the behavior is due to the 0.5 μf condenser in combination with the associated resistors.

XII. Auxiliary Control of Thermally Limited Oscillators

In the Meacham and certain other oscillator circuits a thermistor is associated with reactive elements in a bridge circuit which functions as both limiter and filter. In these circuits a large increase in the frequency stability is observed. This may sometimes be conveniently expressed as a magnification of the effective Q of the filter.

The advantages of great frequency stability and good amplitude stability of these systems are accompanied by an undesirable tendency toward intermittent operation. The thermal constants of the thermistor are not readily adjustable. Moreover adjustment of the reactances to secure

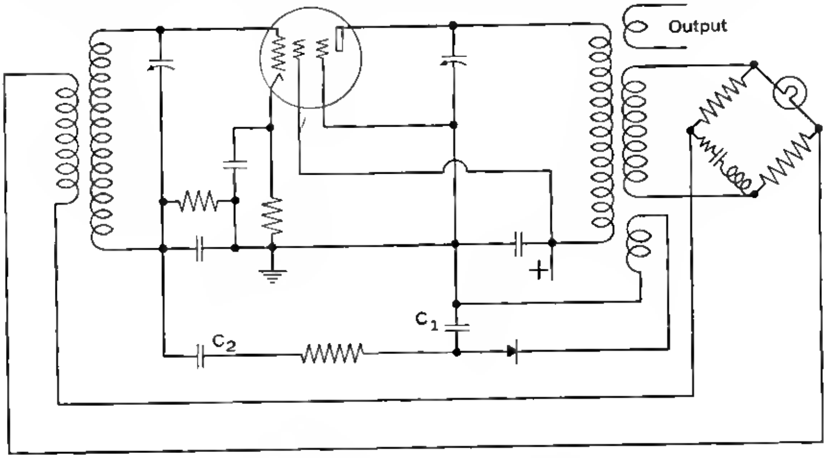

Fig. 26—Meacham circuit with auxiliary control.

suitable envelope stability is likely to impair the frequency or amplitude stability for which the circuit is chosen.

This dilemma may be resolved by the addition of an auxiliary network which does not affect the envelope transmission to very low frequencies but does modify the behavior at higher frequencies in such a way as to promote the stability of the system.

A simple circuit illustrating the principle appears in Fig. 26. It will be noticed that the circuit is so arranged that the average bias applied to the tube is only that due to the cathode resistor. The steady voltage developed across C_1 by the rectifier is unable to affect the bias because of the blocking condenser C_2. Accordingly the rectifier circuit does not affect the normal operating condition, which is characterized by a bridge loss equal to the amplifier gain. The added elements come into play only if there is a tendency toward self-modulation. Then displacement currents of modulation frequency flow through C_2 in such a magnitude and phase as to modify the tube gain and compensate the modulation returned from the bridge.

The exact nature of the control which must be added is best ascertained by opening the circuit at the plate of the tube. The loop transmission of a modulation envelope may then be determined, either experimentally or analytically. If instability is found an auxiliary circuit must be designed to produce an over-all system which is stable. In general the elements of the auxiliary circuit are to be chosen so that the loop transmission is considerably less than unity in the region of zero phase. This is ordinarily accomplished by increasing the final cutoff frequency at which the over-all loop envelope transmission is negligible.

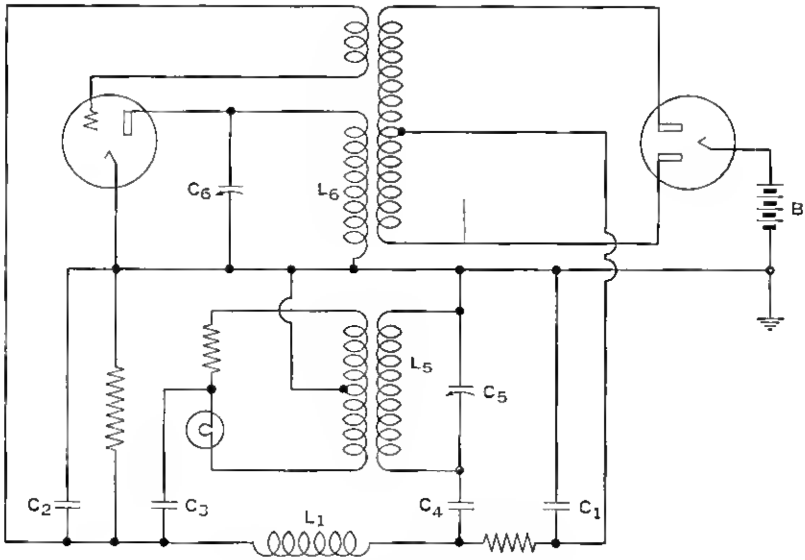

Fig. 27—Self-modulating oscillator.

XIII. A Self Modulated Oscillator

The previous sections have been devoted primarily to the problem of preventing self-modulation in oscillators. Let us now consider an oscillator having envelope instability. The Nyquist diagram indicates that self-modulation will occur and tells the approximate frequency of the envelope wave. More detailed analysis of the circuit is necessary to determine the wave form of the envelope and the manner in which its amplitude is limited.

If a circuit is to function well as an oscillator the Nyquist diagram for the operating frequency must loop the $(1, 0)$ point with considerable margin. This is necessary so that a small loss of gain will not stop oscillation. At the operating level the limiter reduces the loop transmission to unity. In the region of $(1, 0)$ amplitude stability is favored if the rate of change of gain

with respect to level is high. Similarly the frequency stability is favored if the rate of change of phase with respect to frequency is high.

If a circuit is to function well as a self-modulated oscillator, the above conditions must be met and in addition the Nyquist diagram for the envelope must meet similar requirements. That is, there must be a limiter and filter in addition to the effective amplifier in the envelope system.

A circuit which meets these requirements is shown in Fig. 27. It is seen to be similar to that of Fig. 6 but to have a more complicated low-frequency path. The operation is best explained in terms of the relative size of the various elements. The by-pass condensers C_1 and C_2 are comparatively small. The blocking condensers C_3 and C_4 are quite large. The choke L_1 is large. Thus these elements serve as open or short circuits but do not enter into the setting of either of the frequencies.

The stability tests are carried out by opening the mesh at the plate of the tube. At the operating frequency, as defined by the plate coil and condenser the loop gain is high at low levels. Thus the fundamental conditions for oscillation exist.

The next step in the analysis is to supply a signal of suitable magnitude and frequency to reduce the loop transmission to $(1, 0)$. A small modulation of very low frequency is returned magnified and reversed in phase, as with previous systems. The phase of the envelope transmission changes with increase of modulating frequency until it is zero at the resonant frequency of L_5 and C_5. At this frequency a considerable gain exists so that the Nyquist diagram for the envelope also loops the point $(1, 0)$.

The tungsten lamp in conjunction with the other impedances of the bridge serves to limit the degree of self-modulation. The operating frequency may be set by means of C_6 in conjunction with a suitable value of L_6. The operating amplitude may be controlled by adjustment of the bias battery B. The frequency of the self-modulation is set by means of C_5 in conjunction with L_5.

XIV. Conclusions

A method of applying known feedback theory to the problem of self-modulation in oscillators has been presented. Although the discussion has been limited to electrical circuits it is clear that the analysis is applicable to other systems, such as electromechanical or mechanical oscillators.

The analysis has been applied to several familiar oscillators to illustrate the method and to clarify some details of their operation. A sample design of a bias controlled oscillator is presented to show application to new designs.

The application of bias control to thermistor stabilized oscillators is described. The design of a self-modulated oscillator is undertaken to show how intentional modulation may be introduced and controlled.